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We have developed and produced vanadium doped cadmium telluride (CdTe:V) crystals that exhibit the necessary properties for optical power limiting at near infrared wavelengths. The CdTe:V crystals that we have produced exhibit the field shielding effect, have good transmission of low intensity radiation and display high photoconductivity. We have demonstrated the use of these crystals for EOPL at 1.06μm. Furthermore, through device modelling and theoretical calculations, we have developed an innovative design to improve the performance of electro-optic power limiters: the two-stage EOPL. A two-stage EOPL could extend the range of input intensities over which the limiter can operate and improve the dynamic range by three orders of magnitude. We present the theory behind a two stage EOPL, a prototype design of this device, as well as a preliminary evaluation of its performance. A two stage EOPL device represents a new state of the art in EOPL performance.

The EOPL material and device developed during this work have potential uses in both military as well as commercial applications. Commercial applications include two-dimensional signal processing, increasing the dynamic range of sensors and civilian security systems.

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Final Report

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"Optical Power Limiters Using Vanadium Doped Cadmium Telluride (CdTe:V) At Near Infrared Laser Wavelengths"

Phase I Contract DASG60-96-C-0108

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Optical Power Limiters Using Vanadium Doped Cadmium Telluride (CdTe:V) At Near Infrared Laser Wavelengths

Phase I Contract
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Final Report

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Optical Power Limiters Using Vanadium Doped Cadmium Telluride (CdTe:V) At Near Infrared Laser Wavelengths

Final Report

October 1996

1.0 Executive Summary- Phase I

This Phase I research was aimed at producing high quality optical limiting material and an electro-optic power limiting (EOPL) device operating at near infrared wavelengths. During this time period, we have developed and produced vanadium doped cadmium telluride (CdTe:V) crystals which exhibit the necessary properties for optical power limiting, and we have demonstrated the use of these crystals for EOPL. We have also developed an innovative design to improve the performance of electro-optic power limiters. This novel two stage EOPL design can improve the dynamic range of the device by three orders of magnitude and represents a new state of the art in EOPL performance.

For efficient electro-optic power limiting, the material used must contain a high enough concentration of deep level impurities to induce photoconductivity and the field shielding effect. If, however, the concentration of deep levels is too high, then the crystal will exhibit poor transmission. Therefore, the appropriate level of impurities is required to obtain a balance between the transmission of the crystal and the photoconductivity and field shielding properties of the crystal. Additionally, photoconductivity that is due to shallow level impurities results in crystal which exhibit voltage breakdown and a poor mobility-lifetime product. Therefore, it is necessary to ensure that the photoconductivity results from deep level impurities rather than shallow levels.

Within the time period of this Phase I project, we have produced CdTe:V crystals that exhibit the properties necessary for efficient EOPL operation. We have produced crystals that exhibit the field shielding effect, have good transmission of low intensity radiation and display high photoconductivity. However, we believe that there are still improvements that can be made to both the material parameters of CdTe:V and to the device design of the EOPL.

For instance, growth of CdTe often times results in material with a high concentration of complex point defects because of stoichiometric problems. Therefore, further investigations into improving the microstructure of the crystals through growth and processing techniques is necessary to obtain superior EOPL material.

In addition to improving the quality of the crystalline structure, it is also worthwhile to investigate the concentration of the vanadium dopant used to create the field shielding effect in the CdTe. During the six months of this phase I project, we grew CdTe crystals with only two

concentrations of vanadium: $1x10^{19}$ cm^{-3} and $5x10^{19}$ cm^{-3}. In the past, we have seen the field shielding effect in indium doped CdTe with a dopant concentration of only 10^{13} cm^{-3} [1]. Therefore, the effect of using a lower concentration of vanadium in the CdTe crystals should be explored. A lower dopant concentration may increase the transmission through the crystal without degrading the photoconductivity or field shielding properties. Furthermore, the "as-received" vanadium that was used during this project was 99.98% pure. Given the time frame in which we were working, we were unable to further purify the vanadium. Since impurities contained within the vanadium may contribute to increased absorption in the CdTe crystal, purification of vanadium prior to crystal growth should be performed.

During this phase I project, we also evaluated the device performance of an electro-optic power limiter. Even with an optimized material (i.e. good transmission, high photoconductivity, and field shielding properties) and optimum polarizers (i.e. having a high extinction coefficient) the response of an EOPL is still limited in the range of input intensities over which it will perform as a limiter. Through device modelling and theoretical calculations, we have developed an innovative design that could extend the range of input intensities over which the limiter can operate. This innovative design is a two-stage EOPL. This report contains the theory and prototype design of this two-stage EOPL, as well as a preliminary evaluation of its performance. This innovative technique requires much further examination and could greatly improve the current technology of electro-optic power limiters.

2.0 Introduction

An optical power limiter is a device that responds non-linearly to incident radiation and prevents the transmission of high intensity light. Optical limiters are used for the protection of optical and electro-optical detectors from high intensity jamming beams of radiation. There are also numerous applications in the field of optical signal processing where a limiter can be used to expand the dynamic range of a sensor. The approaches to optical limiting in the past have varied. Kerr liquids and liquid crystals have been used as optical limiters by utilizing self-focusing [2] and two-photon absorption [3], respectively. Limiters using semiconductors have been produced that rely on excited state absorption, such as silicon [4], or a combination of two-photon absorption and self-defocusing, such as gallium arsenide [5]. Beam fanning in photorefractive materials has also been utilized in the production of optical limiters [6,7]. These approaches are usually based on the incidence of very high irradiance levels and therefore, the limiting material must be positioned at the focal point of the optical system. This positioning seriously limits the optical interaction length of the material causing many of the proposed devices to be ineffective and inhibiting the use of the device for two-dimensional optical limiting. Additionally, these photorefractive limiters only work with coherent radiation. This condition places serious limits on the usefulness of such a device. It is also very easy to destroy the coherence of incident radiation with the addition of a chirp to the signal.

The ideal optical power limiter should completely block jamming radiation above a predetermined threshold. In doing so, it must [7]:

(i) be sensitive over the desired spectral range;
(ii) transmit the desired radiation;
(iii) have a large field of view;
(iv) provide protection against both continuous and pulsed radiation;
(v) be capable of blocking radiation from multi-wavelength sources; and
(vi) be capable of blocking incoherent radiation.

During this research, we have developed an electro-optic power limiter (EOPL) based on the II-VI semiconductor cadmium telluride (CdTe). An EOPL, which operates on the basis of photoconductivity in an electro-optic material, was first demonstrated by Steier et al. [1]. This device possesses many desirable capabilities and has been shown to be superior to the previously used methods described above [8]. First, EOPL devices can achieve ultrahigh sensitivity to extremely low intensity light. This sensitivity and the arbitrarily long interaction length of charge transport media provides a response that saturates at intensity levels on the order of a few milliwatts per square centimeter. It is also a self-actuating device that turns on automatically and does not require external feedback circuitry. An EOPL device can have a field of view as wide as 10° full angle depending on the device design and the dispersion of the crystal. Finally, the device is insensitive to the phase of light and therefore can be used to limit both coherent or incoherent light.

Although the concept of EOPL has been known for a few years, the development of devices has been hampered because of the lack of suitable material. Brimrose Corporation has developed several materials which display electro-optic power limiting. Vanadium doped zinc telluride (ZnTe:V) is a relatively new photorefractive material developed exclusively by Brimrose in collaboration with the Center for Photonics Technology at the University of Southern California [8,9]. With proper modifications of the dopant concentrations, this material can be tailored for optical limiting. We have demonstrated that ZnTe:V exhibits field-shielding non-linearities over the wavelength range of 0.63 to 1.3μm [10].

We have also shown the feasibility of producing optical power limiters using photorefractive vanadium doped cadmium manganese telluride crystals (CdMnTe:V) [11]. The CdMnTe:V crystals that we have produced for this purpose, however, have typically exhibited a high degree of strain induced birefringence possibly as a result of twinning in the crystal. This material is currently being developed further under an SBIR contract through the Air Force with Dr. Patrick Hood as the technical monitor [12].

Recently, Brimrose has developed vanadium doped cadmium telluride (CdTe:V), a relatively new class of photorefractive materials, which can be used for optical limiting at near infrared wavelengths with proper modification. Our previous experimental results [1,8,13-16] showed that if a CdTe crystal exhibited good photoconductivity and had effective doping levels on the order of 10^{16} cm^{-3}, then the material was photorefractive. On the other hand, if the dopant concentration was in the range of 10^{12} to 10^{13} cm^{-3}, then it was found to exhibit excellent limiting properties. To the best of our knowledge, Brimrose Corporation, in collaboration with Dr. Steier's research group at the Center for Photonics Technology at the University of Southern

California, is the only company in the country to develop CdTe:V which can be tailored to function either as a photorefractive material or an EOPL.

Steier et al. [1,17] have demonstrated power limiting and self-switching caused by the field shielding effects of charge created by photoconductivity at 1.06 μm in indium doped CdTe (CdTe:In). The CdTe:In exhibited a relatively low threshold of approximately 100 $\mu W/cm^2$ and switching times on the order of microseconds over wavelengths from 0.9 to 1.3 microns. These figures represent performance that is far better than that which can be achieved using conventional limiting materials. There are several drawbacks, however, to using indium as the dopant in CdTe to produce the field shielding effect. Indium generates complex stoichiometric defects in the crystalline structure and increases the concentration of cadmium vacancies. Additionally, indium doped as-grown crystals can be either conducting or semi-insulating according to the indium doping levels, oftentimes making it necessary for post growth heat treatment. It is also difficult to control the concentration of deep level traps in the CdTe band structure and therefore, the performance of CdTe:In is often limited by a relatively low density of electron traps.

Brimrose Corporation has found that vanadium doped CdTe exhibits better photorefractive properties as well as increased resistivity and photoconductivity compared to the indium doped crystals. As such, optical limiters made from CdTe:V have even better response time and higher damage thresholds. We believe, therefore, that CdTe:V represents a promising candidate for use in high performance optical limiters at infrared wavelengths. From an operational and device point of view, the EOPL based on this material does not require extensive external optical systems which are typically required in almost all other limiters. We believe that this device represents a new state of the art in optical limiters.

3.0 Background

3.1 EOPL Operation

EOPL operates on the basis of a combination of the electro-optic and the photoconductive effects. This phenomenon, referred to as the field shielding effect, is illustrated in Figure 1. An incident beam creates a conduction band electron density by the excitation of carriers from deep level impurities. An applied electric field causes these electrons to drift into the adjacent dark regions of the crystal where they are subsequently trapped. The resulting negative charge density in the dark region and the compensating positive charge density in the illuminated region create a space-charge electric field which is opposite to the applied field. Equilibrium conditions are reached when the flow of electrons from the illuminated region into the traps is balanced by the thermal reionization of the traps. These reionized electrons can then contribute to the current flow. Thus, at low intensities, only a small amount of charge is trapped and the field seen by the incident beam is the applied field. At higher intensities, however, a larger space charge accumulates which will balance the flow of electrons into and out of the traps, and the incident light sees only a small remaining field. This phenomenon is very similar to the intensity dependence of the photorefractive effect described by Townsend and LaMacchia [18].

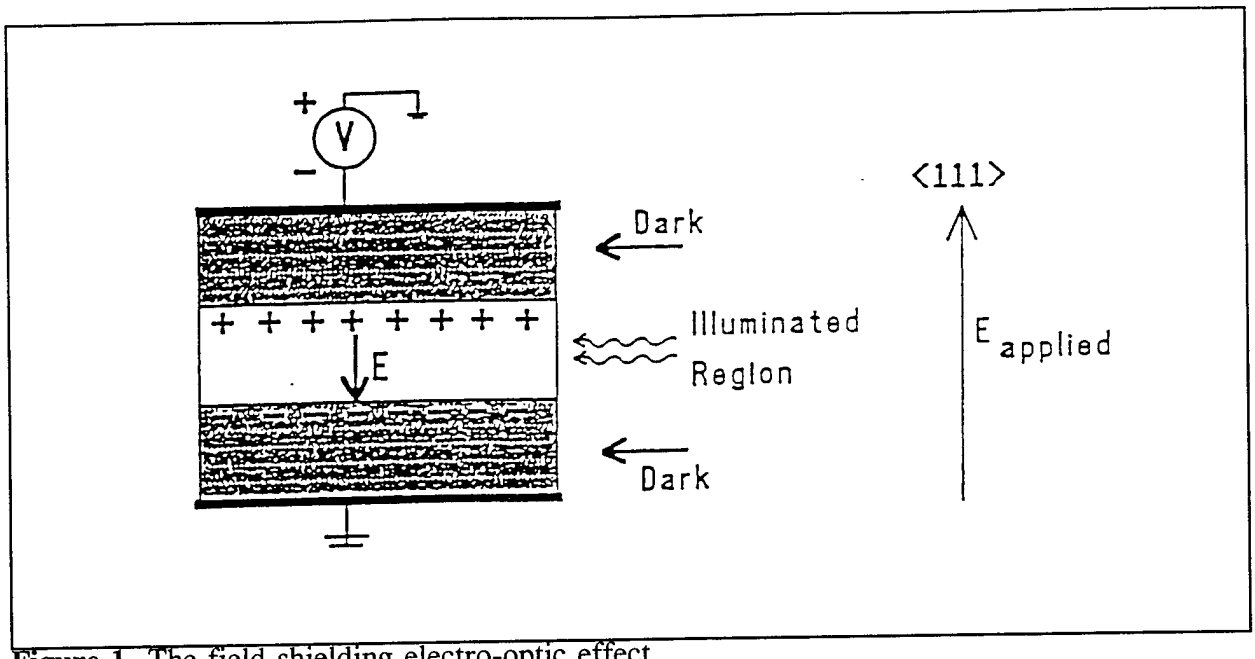

Figure 1 The field-shielding electro-optic effect

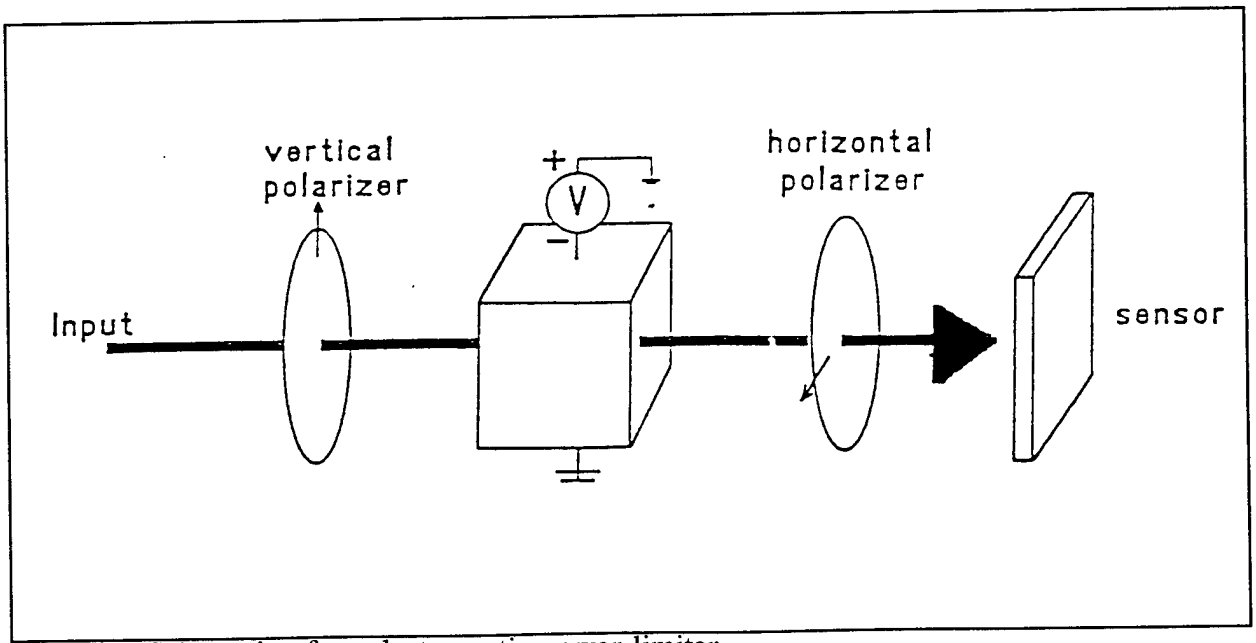

Figure 2 Schematic of an electro-optic power limiter.

Figure 2 shows the basic components of an electro-optic power limiter which utilizes a

material that exhibits the field shielding effect described above. The CdTe:V crystal is sandwiched between two crossed polarizers. During operation, a voltage is applied to the crystal such that the electro-optic effect will cause the polarization of a low intensity incident beam to undergo a 90° rotation and therefore, pass through the second polarizer. Conversely, when high intensity light is incident on the device, the illuminated region will be electrically shorted due to the photoconductive nature of the limiting crystal and will not undergo any rotation of polarization. This high intensity light will not be transmitted through the second polarizer and is blocked from the sensor. **The device will simultaneously block a high intensity jamming beam of laser radiation while still transmitting the desired low intensity light.**

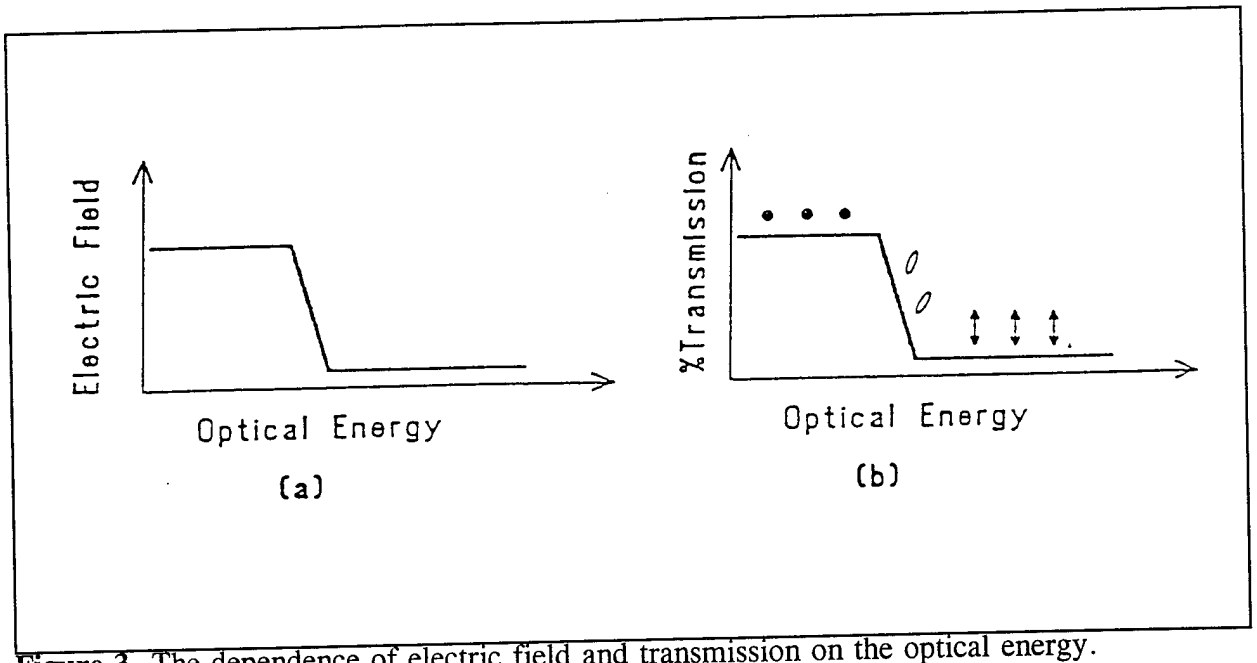

Figure 3 The dependence of electric field and transmission on the optical energy.

Under ideal conditions, the amplitude of the electric field that results when optical energy is incident on the limiter is shown in Figure 3a. The polarization of the incident beam is altered according to this field. As a result of the field shielding phenomenon, the polarization state of the light and the transmission intensity through the polarizer both depend on the intensity of the incoming light. The polarization and transmission are plotted versus input optical energy in Figure 3b. In practice, however, there is some leakage of light through the optical limiter due to a number of factors, including non-ideal polarizers, crystalline imperfections and strain induced birefringence in the crystal.

3.2 Material Parameters

Several material parameters must be considered when choosing a suitable material for electro-optic power limiting. First, the wavelengths over which the crystal will respond is dictated by the energy band diagram, shown in Figure 4. The minimum energy necessary for photoionization is the energy difference between the deep trap level and the bottom of the

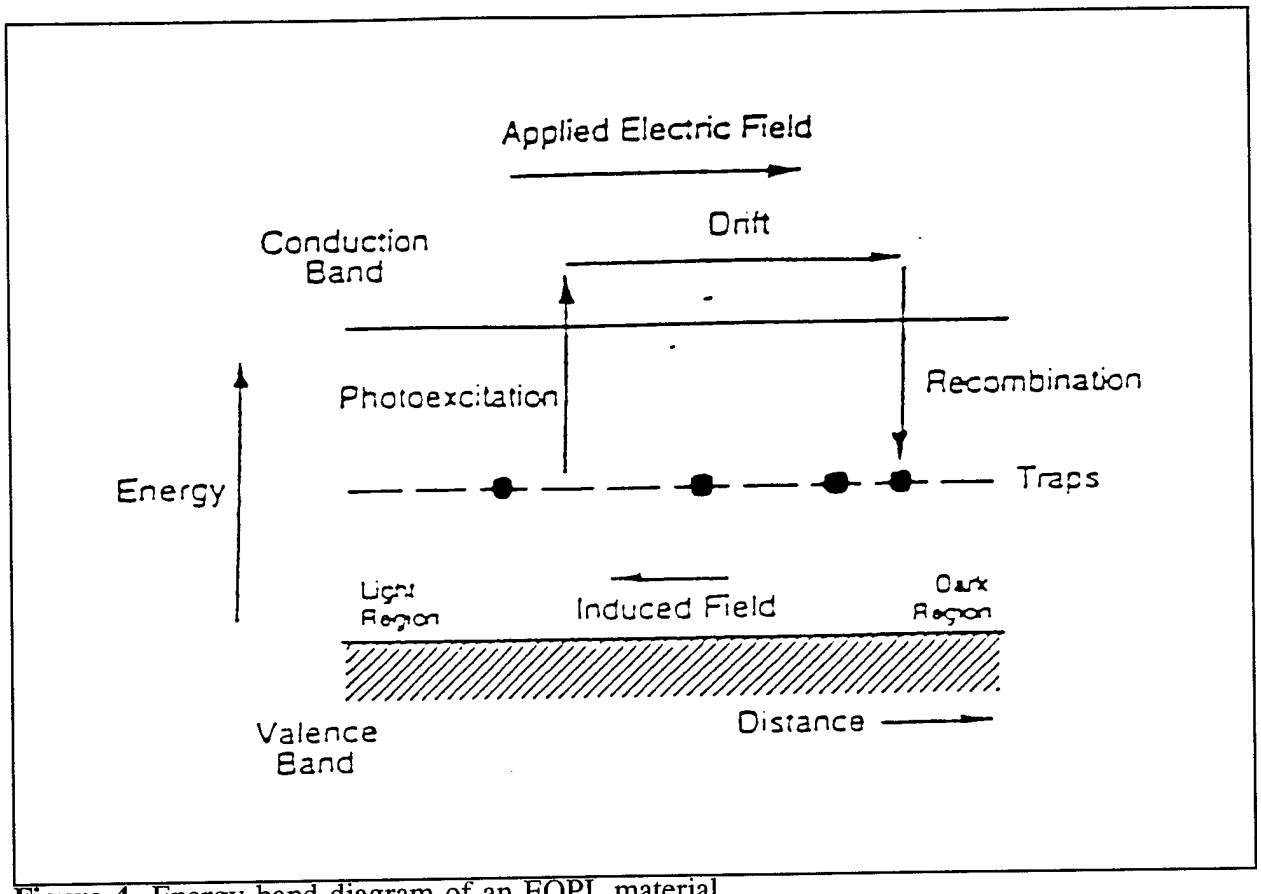

Figure 4 Energy band diagram of an EOPL material.

conduction band. The photon energy can be larger, but it can not exceed the band gap energy. Therefore, the EOPL will respond to wavelengths within this range of energies, and it is said to have *wide-band wavelength responsivity*.

Although transmission over the desired wavelength range must be high, the shape of the transmission curve as a function of wavelength is crucial: The transition from low transmission to high transmission at the bandgap must be gradual. To illustrate this property, Figure 5 shows the transmission curves of several CdTe and CdMnTe samples that have been investigated previously. The samples corresponding to curves 5, 6 and 7 exhibit extremely low transmission and therefore, can not be used as optical limiters. Although curves 1, 2 and 4 represent crystals with adequate transmission, they exhibit a very sharp transmission edge. These crystals will not

exhibit adequate field shielding effect or photorefractivity and also can not be used for optical limiting. Only the crystal corresponding to curve 3, which shows a gradual change in transmission over several hundred nanometers, displays the appropriate transmission characteristics and field shielding properties for an optical limiting material.

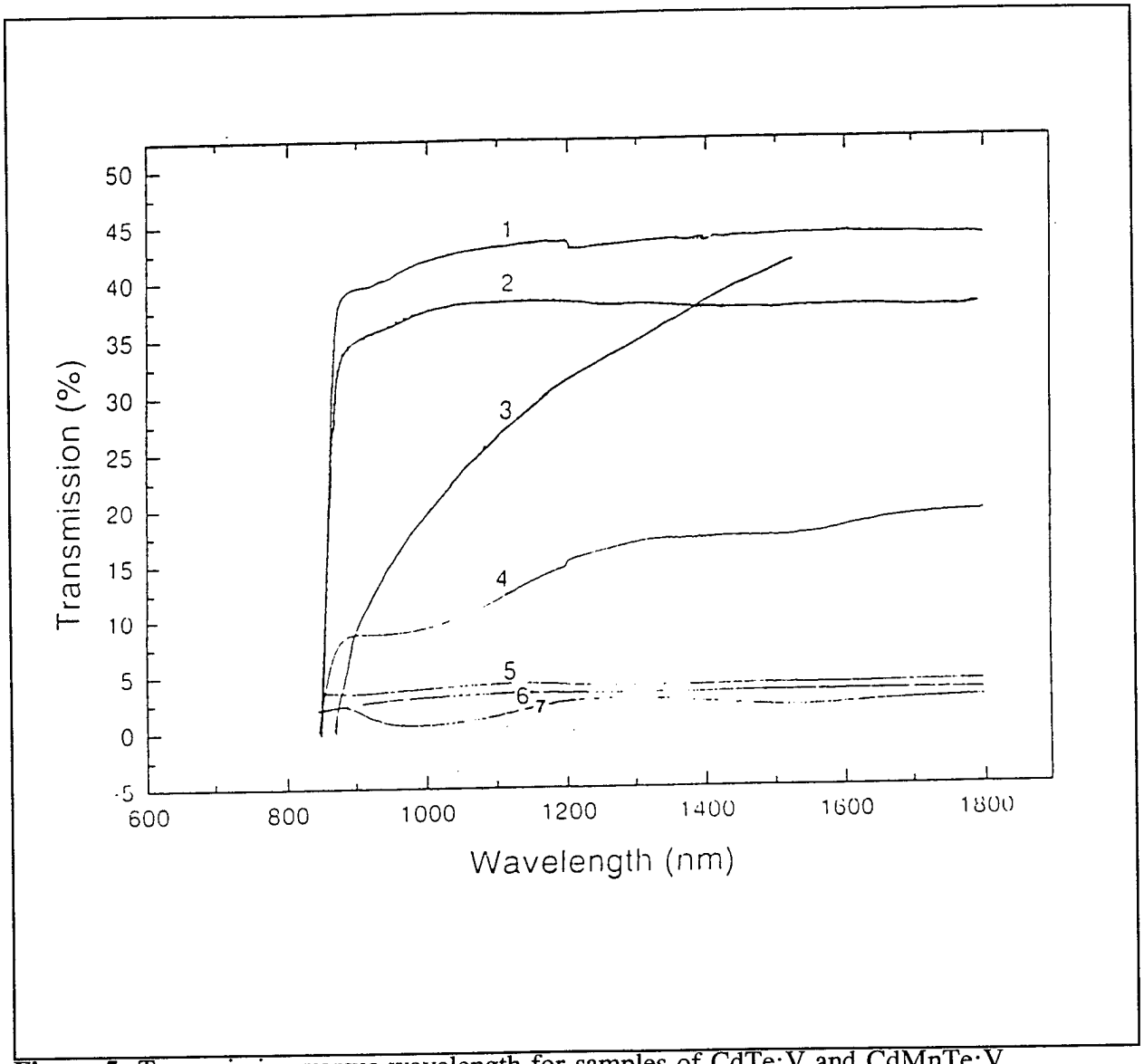

Figure 5 Transmission versus wavelength for samples of CdTe:V and CdMnTe:V.

Another important material parameter is the dark conductivity. During the build up of the induced electric field, there is competition between the photoionized and thermally ionized carriers. In order to have an EOPL with low threshold power, the thermally ionized charges must be minimized so that the crystal has a low dark conductivity. Therefore, the concentration of shallow energy levels and defect levels should be minimized and the crystal should be of high crystalline quality.

When choosing a material with appropriate wavelength responsivity and low dark conductivity, a crystal with cubic symmetry is preferred. Non-cubic crystals naturally exhibit birefringence in which light propagating though the material will split into an extraordinary and an ordinary component. For optimal EOPL operation, birefringence should only occur when induced by an electric field. On occasion, some EOPL crystals exhibit strain induced birefringence which causes non-optimal performance of the device. This topic will be discussed later in this report.

Those criteria that are applicable to electro-optic modulators are also required of a crystal that is to be used as an electro-optic power limiter. The figure of merit for electro-optic materials, $n_o^3 r_{41}$, where n_o is the refractive index and r_{41} is the electro-optic coefficient, must be high. The value of $n_o^3 r_{41}$ directly affects the half wave voltage (V_π) of the crystal. The half-wave voltage for a crystal with an interaction direction along the $<110>$ crystallographic axis of the crystal is:

$$V_\pi = (\lambda/2)(D/L)(1/n_o^3 r_{41})$$

where D is measured along the direction of the applied field and L is measured along the propagation direction of the light. For minimization of this value, the aspect ratio (D/L) must be low and $n_o^3 r_{41}$ must be high.

Along with a high electro-optic coefficient, an EOPL material should exhibit a long mobility-lifetime measurement (ie, electron mobility and recombination lifetime product) in order to achieve the high speed of operation. These intrinsic properties can be optimized through growth of material with the highest possible crystalline quality. A low concentration of line defects in the crystal and a low concentration of point defect impurities, both native and foreign, is crucial for high crystalline quality. Extrinsically, the material should be doped so as to achieve a large amount of photoconductivity. Both the concentration and the nature of the dopant are essential in determining this characteristic. Additionally, the dopant must be homogeneously distributed throughout the crystal for optimum photoconductive performance.

Two critical issues for field shielding limiters is the response time and the intensity threshold of the devices. The response time gives an indication of the protection the limiter can provide to pulsed radiation and the intensity threshold indicates the lowest intensity levels at which limiting is possible. These two parameters provide guidance for the materials development and indicate the materials parameters of importance. It can be shown that the response time or the time required for the limiting to reach 50% of the maximum limiting is given by,

$$T = [\ \epsilon h\nu/eI\ ]\ \ 1/\mu\tau_o\eta\alpha$$

The intensity threshold, which is the optical intensity required to limit the output to 50% of the low intensity value, can be shown to be,

$$I_T = A \ [\ 1/\mu\tau_o\alpha\tau_d\eta \ ] \ \epsilon h\nu/e$$

In these expressions,

- ϵ = dielectric constant
- e = electron charge
- h = Planck's constant
- ν = optical frequency
- I = optical intensity
- μ = carrier mobility
- τ_o = carrier lifetime in the illuminated region
- τ_d = carrier lifetime in the dark region
- η = quantum efficiency of the light absorption, i.e., the percent of absorbed photons that produce charge carriers
- α = absorption coefficient at the limiting wavelength
- A = a geometrical factor.

From these expressions, we see that the material parameters which control the sensitivity and the response time are the charge mobility, the carrier lifetime, the absorption coefficient and the quantum efficiency. The charge mobility and the carrier lifetimes are strongly influenced by the stoichiometric native defects and impurity levels in the material.

3.3 EOPL Model

The transmission behavior of an EOPL can be analyzed using a simple model [19]. The diagram used for this model is shown in Figure 6.

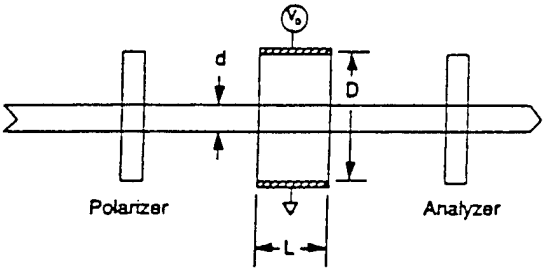

Figure 6 Diagram used for EOPL model.

In this model, the total conductivity σ is taken to be linear with the input intensity I_{in}:

$$\sigma = \sigma_{dark} + \beta I_{in} \tag{1}$$

where the photoconductivity $\sigma_{photo} = \beta I_{in}$. Assuming that the beam has a square profile, the voltage drop V_{photo} across the light region can be easily found using a voltage divider

$$V_{photo} = \frac{V_o}{1 + (1 - D/d)(1 + \sigma_{photo}/\sigma_{dark})} \tag{2}$$

Eq. 2 describes how the field across the light region (V_{photo}/d) decreases when I_{in} (hence σ_{photo}) increases. Using Eqs. (1) and (2), the output intensity for $V_o = V_\pi$ is found to be:

$$I_{out} = I_{in}\{ \sin^2 [\frac{\pi / 2}{1 + (1 - d/D)(\beta/\sigma_{dark})I_{in}}] + \epsilon_p\} \tag{3}$$

where ϵ_p is the extinction ratio of the polarizers. From Eq. (3) we see the importance of the material parameter β/σ_{dark}: the higher this ratio, the better the limiting performance.

Eq. (3) shows that there are two ways to improve the performance of an optical limiting device: minimize σ_{dark} or increase β. The former can be accomplished by minimizing shallow levels and by compensation, and the latter by increasing the concentration of the deep level impurities and controlling the stoichiometric native defects. However, the deep level impurity concentration must be limited below a certain level to avoid strong absorption in the crystal. Other imperfections that degrade the transmission in the crystal, such as precipitations, should also be minimized to ensure a low insertion loss.

The response time of the limiter is determined by the RC time constant of the illuminated region, (i.e. how long it takes for the fields to redistribute within the crystal):

$$\tau_{response} = (\epsilon_r \epsilon_o) / (\beta I_{in}) \tag{4}$$

where ϵ_r is the relative dielectric constant. From expressions (3) and (4), it is clear that the response time and the sensitivity can be reduced by increased β. The photoconductivity constant β can be written as:

$$\beta = es(\mu\tau)N_D$$

where: e=electron charge; s=photoconductivity cross-section; μ=charge carrier mobility; τ=carrier lifetime; N_D=the density of states responsible for the photoconductivity. From this expression, it can be seen that high carrier mobility and lifetime are needed.

For CdTe, the half wave voltage of a crystal in the (110) orientation is V_π=4.9kV at 1.06μm when D=L. The only way to decrease V_π is to increase L and/or decrease D. However, a longer L leads to a higher insertion loss, and a shorter D leads to smaller throughput (i.e., smaller view angle and beam size). Also, a small D decreases the factor 1-d/D in Eq.(3), and thus, degrades the performance of the limiter. Therefore, D should be reasonably large ($\geq$ 5mm). Consequently, it is advantageous to use higher V_π in order to reduce L and hence, reduce insertion loss. It is reasonable to choose V_π for L=D (i.e., 4.9kV). This voltage is typical in electro-optic devices and is easy to handle.

4.0 Experimental

4.1 Purification, Synthesis and Crystal Growth

Both intrinsic and extrinsic defects affect the opto-electronic properties of CdTe. In order to improve the producibility of high quality crystals, extensive purification of the constituent elements, cadmium and tellurium, was carried out. The received elements were 99.9999% pure. Both cadmium and tellurium have relatively low melting points of 320°C and 450°C,

respectively, and relatively high vapor pressures at low temperatures. Therefore, both vacuum distillation and sublimation were used for further purification. In order to prevent the transfer of the non-volatile or less volatile impurities in the condensation region, sublimation of these materials was not carried out to completion.

For synthesis of CdTe, the purified starting materials were carefully weighed in correct stoichiometric proportions and placed in graphitized fused silica ampoules (approximately 20cm long and 20mm in diameter). For the doped crystals, vanadium was added so that the starting concentration of the dopant was $1x10^{19}$ atoms/cm^3. After being vacuum sealed, the ampoules were placed in a three zone Bridgman furnace. The temperature of the furnace was controlled as follows: 1) increased to 600°C in two hours and held constant for 12 hours; 2) increased to 1125°C over 24 hours; 3) held constant and allowed to react and mix for 24 hours; 4) decreased to room temperature over a 24 hour period.

Crystal growth of CdTe:V was carried out using the vertical Bridgman technique, shown in Figure 7. The synthesized ingots were removed and cleaned in a bromine in methanol

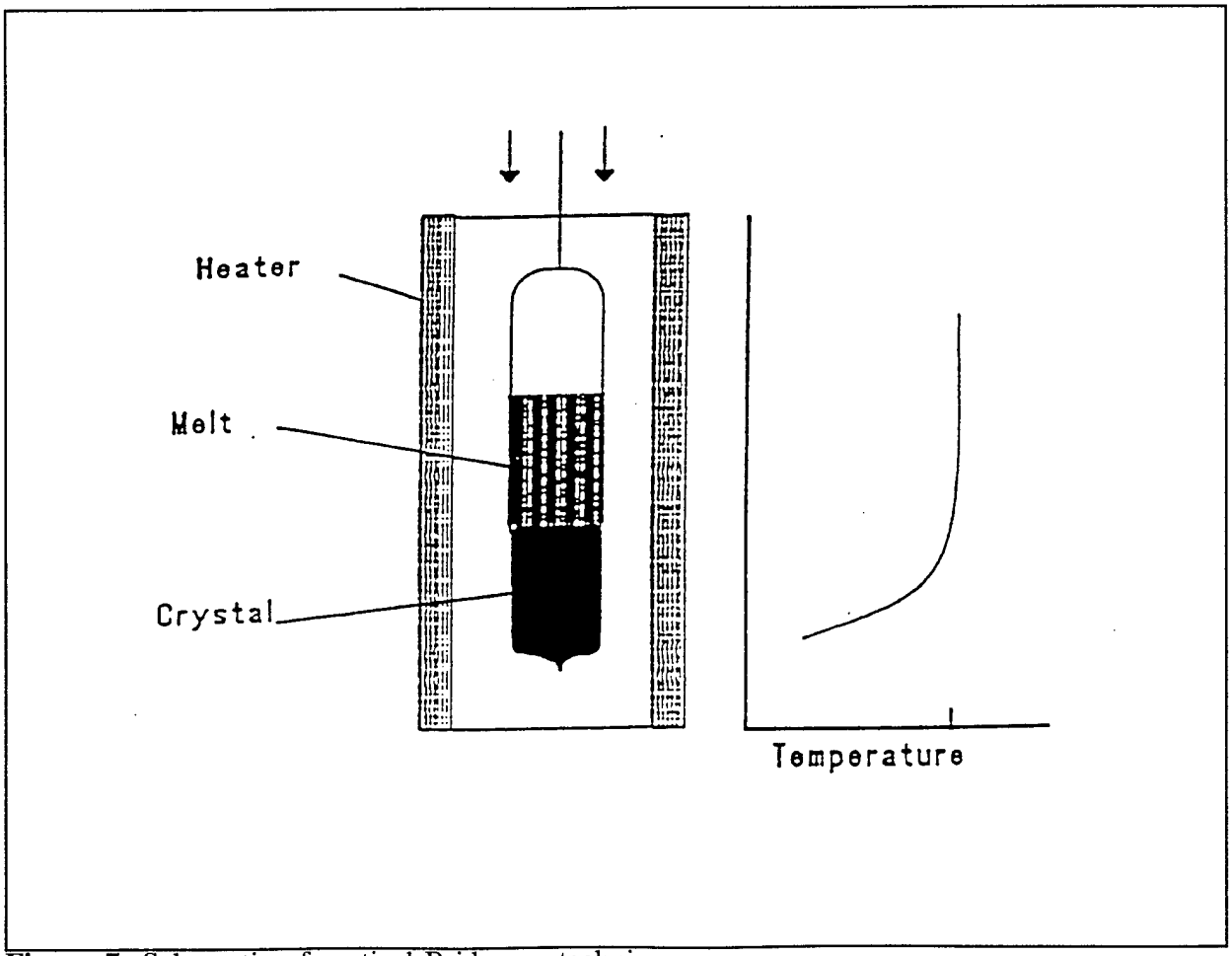

Figure 7 Schematic of vertical Bridgman technique.

solution and resealed under vacuum in graphitized fused silica ampoules. The individual ampoules were again placed in the Bridgman furnace and the temperature was increased to 1125°C in 24 hours. The material was kept in the molten state for approximately 24 hours. Crystal growth was started by translating the ampoule down across the temperature gradient. The translation rate was 2mm/hour and the temperature gradient was 20°C/cm (4°C/hour). After solidification was complete, the boule was kept at a temperature between 925°C and 975°C and allowed to anneal for a period of 48 hours. Finally, the temperature of the furnace was brought to room temperature at a rate of about 1°C/min.

4.2 Characterization Techniques

Several techniques were used to characterize the CdTe crystals grown during this project. Prior to optical limiting measurements, the following material properties were measured: resistivity, photoconductivity, transmission and absorption. Those crystals that were found to be suitable material for optical limiting based on these measurements were then tested for their optical limiting capabilities.

Often, the measurement of high resistivity semiconductors is difficult and may be erroneous due to non-ideal conditions such as current leakage (which leads to an under estimation of resistivity) or contact problems (which leads to an over estimation of the resistivity). Hall measurements using the Van der Pauw technique on samples such as this will typically indicate high resistivity, but the actual determination of resistivity is beyond the limit of the instruments used. Therefore, we used an alternative method to measure the electrical properties of the CdTe:V crystals in which the crystal was placed in series with a known and thermally stable resistor in a simple circuit. A simultaneous measurement of the applied voltage and the voltage drop across the resistor was used to determine the current in the circuit. This current and the known applied voltage was then used to determine the resistance of the crystal. This method permits higher applied voltages than can be used in the Van der Pauw technique. The higher applied voltage has two advantages: 1) the series current is scaled up to values that are easily measured; and 2) the voltage significantly exceeds the "junction potential" and back biasing effects are avoided. The nature of contacts made using silver paste can be non-ohmic and produce erroneous values at low voltages. Using this technique, the applied voltages will be kept below the threshold value for the saturation of the drift velocity.

The photoconductivity of the CdTe:V crystals was also measured. The same apparatus used for the resistivity measurements will be used and the photoconductivity will be determined by measuring the crystals resistivity under dark conditions and under illumination. High photoconductivity is desirable since it indicates a high concentration of mid-bandgap level trap sites and the potential for superior limiting performance.

The optical absorption of the crystals was measured with the use of a Perkin-Elmer Model 337 Grating Infrared Spectrophotometer or a Perkin-Elmer FTIR spectrometer. Occasionally, absorption at a particular wavelength was determined by measuring transmission of laser radiation through the crystal.

4.3 Optical Limiting Measurements

The measurements to determine the limiting capabilities of the CdTe:V crystals were carried out at Brimrose Corporation and at the Center for Photonic Technology at the University of Southern California. The measurement apparatus that was used is similar to that shown in Figure 2, and the limiting experiments were performed as follows. A field was applied across the [111] faces of the crystal. The input light was polarized at 45° to the field, and the analyzer was oriented perpendicular to the input polarizer. The power incident on the crystal after the input polarizer was compared to the light exiting the analyzer and the ratio was normalized to the transmission of the crystal and the analyzer. These measurements were performed using input radiation from a diode pumped Nd:YAG laser with a wavelength of 1.06 μm.

For most of the optical limiting experiments, the applied voltage was fixed and the normalized transmission was measured versus the input intensity. In some cases, however, the input intensity was fixed and the normalized transmission was measured as a function of applied voltage.

5.0 Results and Discussion

5.1 Crystal Growth

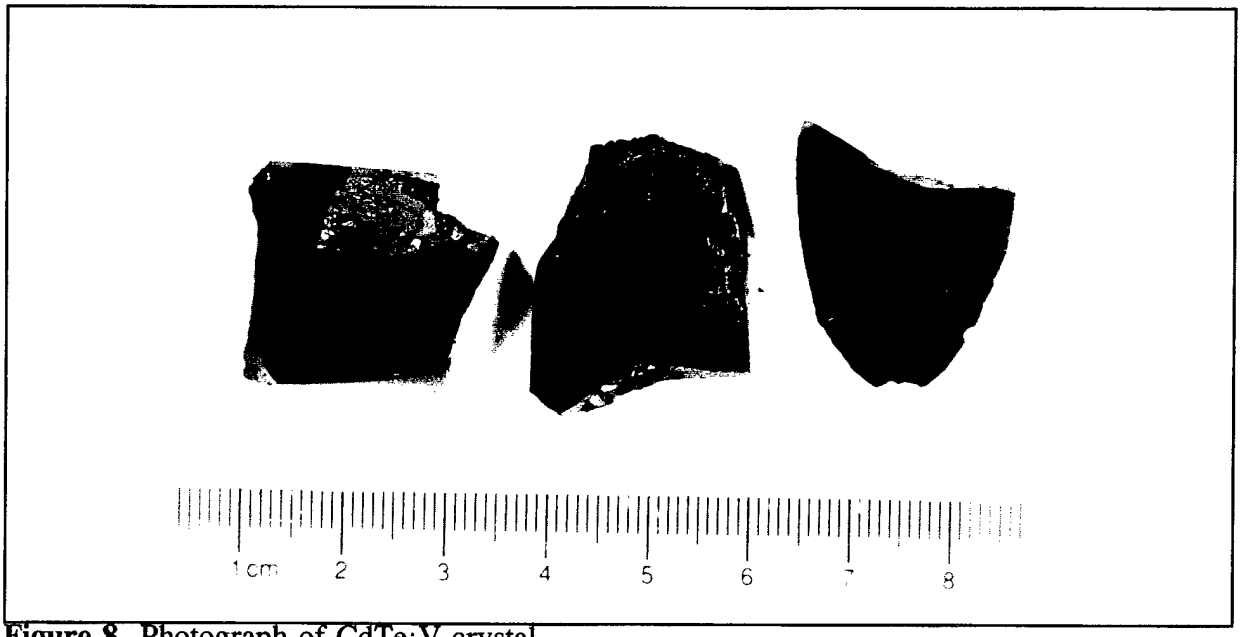

Figure 8 Photograph of CdTe:V crystal.

During this project, several crystalline boules of CdTe:V were grown. A photograph of one of these crystals is shown in Figure 8. The crystals in this photograph were single

crystalline. An example of wafer-like pieces that were cut from a single crystalline section of a different boule are shown in Figure 9. The cleavage planes are clearly seen in these photos.

The crystals were oriented using x-ray diffraction. An example of a Laue pattern of the [110] optical face from one of these crystals is shown in Figure 10. The size and shape of the Laue spots are indicative of good quality crystals. Samples were cut with an orientation of <111> x <110> x <221> and mechanically lapped and polished. The individual crystal samples were then used for further analysis and optical limiting measurements.

5.2 Structural Analysis

Infrared microscopy was used for examination of the crystalline structure of the samples.

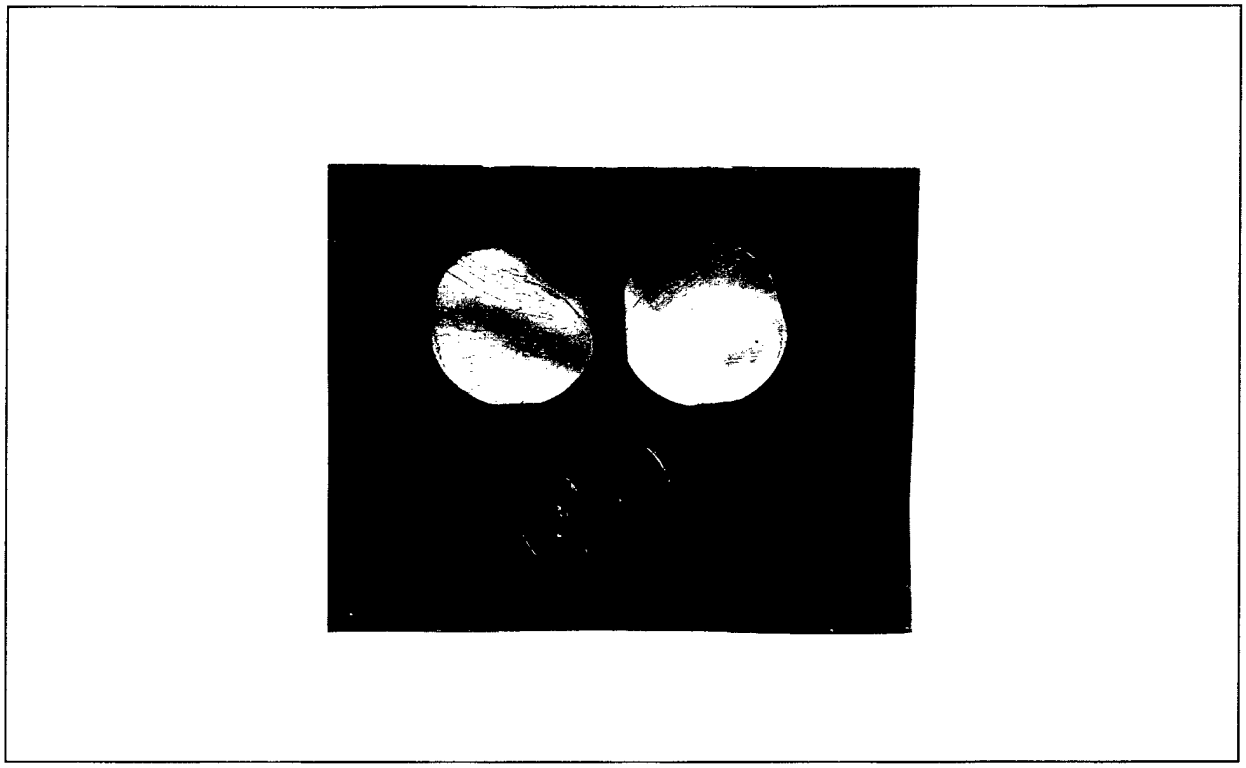

Figure 9 Cross sections of CdTe:V crystal.

With an infrared microscope we were able to view the surface and the bulk of the crystals.

Pictures taken within the bulk material of a CdTe:V crystal are shown in Figure 11. These photos show the presence of precipitates and inclusions within the bulk of the crystal. (The scratch-like marks in the photo on the left are surface marks that had carried through into the bulk). For comparison purposes, we also examined a CdTe substrate that we obtained from

a commercial supplier. Pictures taken using the IR microscope of the bulk of this sample clearly show the presence of a fairly high concentration of precipitates. The pictures are also very "foggy" in appearance indicating lower crystalline quality compared to the CdTe crystals grown at Brimrose during this project.

5.3 Electrical and Optical Characterization

The electrical resistivity of the CdTe crystals were measured using the method described in section 4.2. The resistivity of the crystals under dark conditions were found to be between 10^8 to 10^{10} Ω-cm. These values were sufficiently high for optical limiting materials. The resistivity decreased significantly in the presence of illumination indicating that the crystals were highly photoconductive. As mentioned earlier in this report, photoconductivity is a desirable characteristic for optical limiting materials.

The absorption coefficient of the CdTe crystals were typically between $3cm^{-1}$ and $4cm^{-1}$ over the wavelength range of interest. Plots of transmission and absorption coefficient versus wavelength for a CdTe crystal are shown in Figure 12. The gradual change in transmission with wavelength indicates that this sample exhibits photorefractive properties and is suitable for use as an optical limiter.

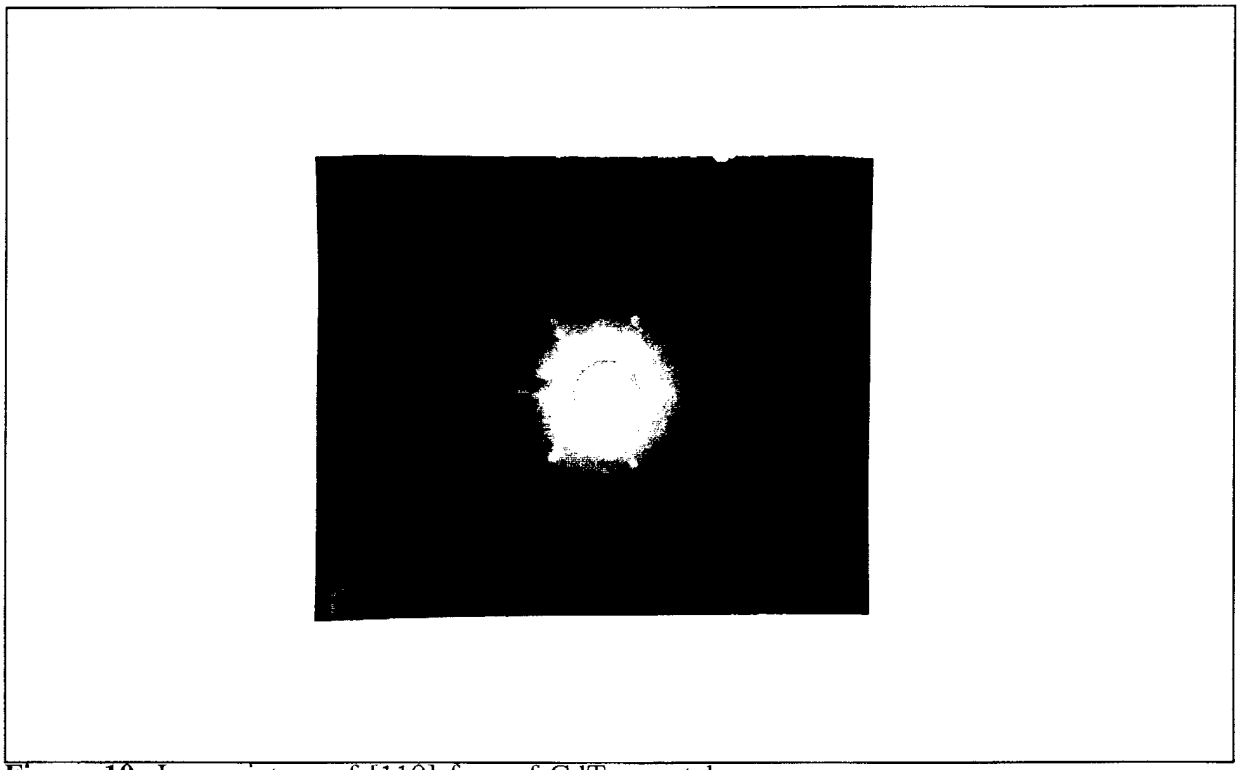

Figure 10 Laue picture of [110] face of CdTe crystal.

5.4 Optical Limiting Measurements

The CdTe:V crystals grown during this project exhibited good optical power limiting performance. The crystal that exhibited the best optical power limiting was 4.5mm x 4.5mm x 6mm. Several measurements were performed on this crystal throughout the course of this project.

In the first experiment, the voltage was applied across the [111] faces which were 4.5mm apart. The normalized transmission as a function of input voltage was measured along both the short (4.5mm) and long axes (6mm) of the crystal. These results are shown in Figure 13 for input intensities of 13 mW/cm^2 and 65 mW/cm^2. Because of voltage limits on the power supply, it was only possible to achieve a full half wave of retardation by traversing the long dimension of the crystal with low to moderate intensities. We also experienced occasional problems at high intensities and high voltages because the increased photoconductivity of the crystal caused the sample to draw enough current to overload the power supply. This problem and its solution will be discussed later in this report.

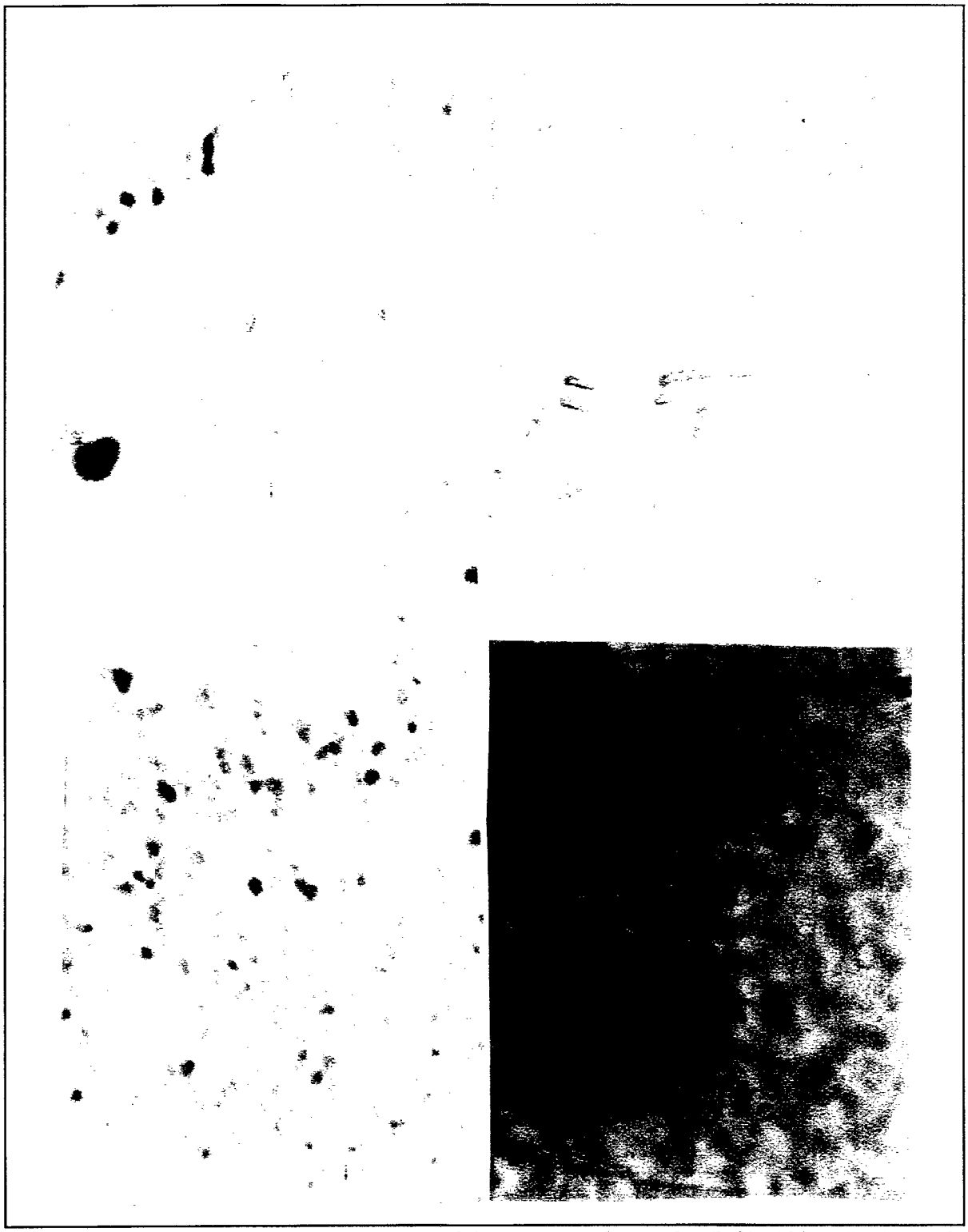

Figure 11 Infrared microscopic photos CdTe:V crystals; scale (left)=100μm/inch, scale (right)=50μm/inch.

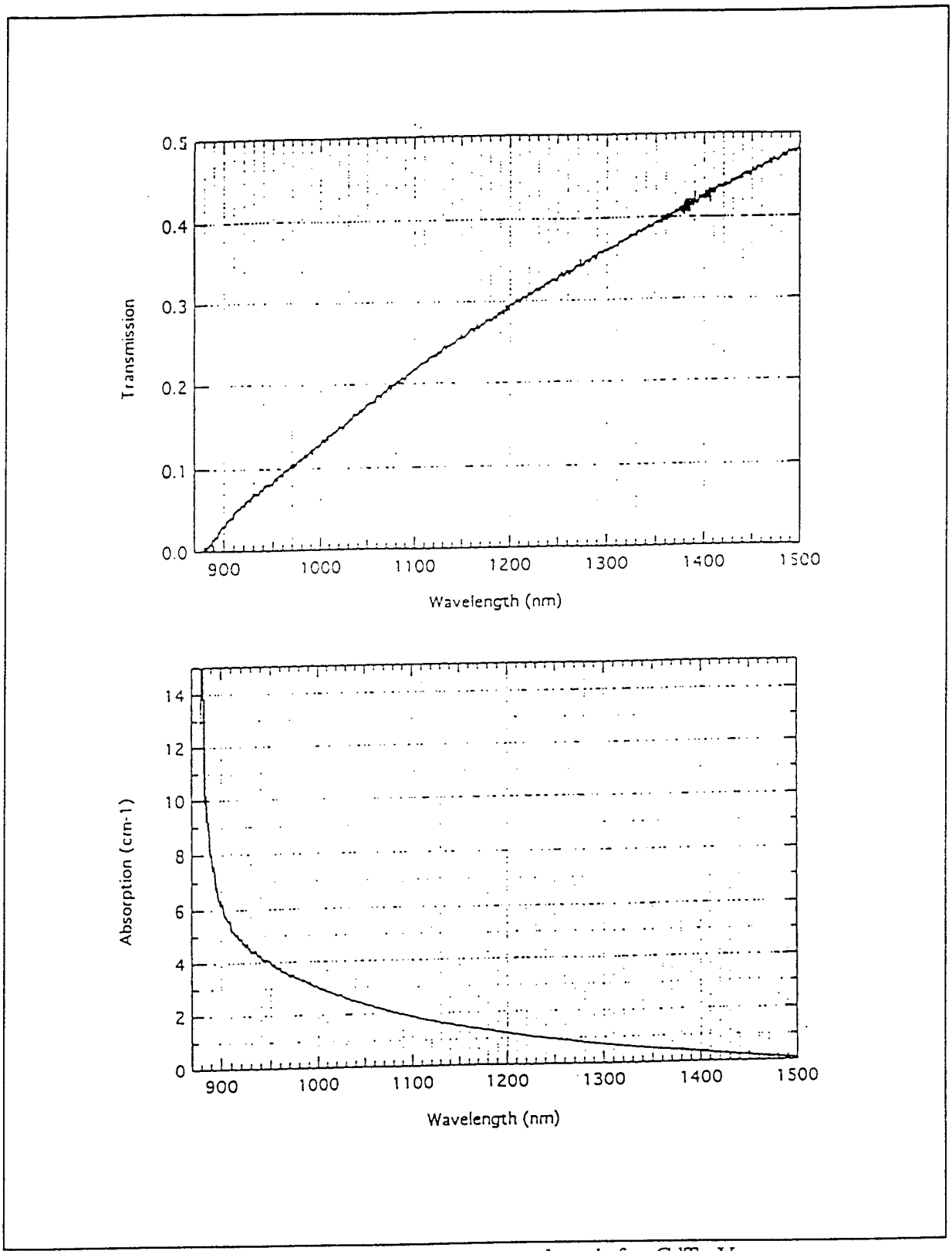

Figure 12 Transmission and absorption versus wavelength for CdTe:V.

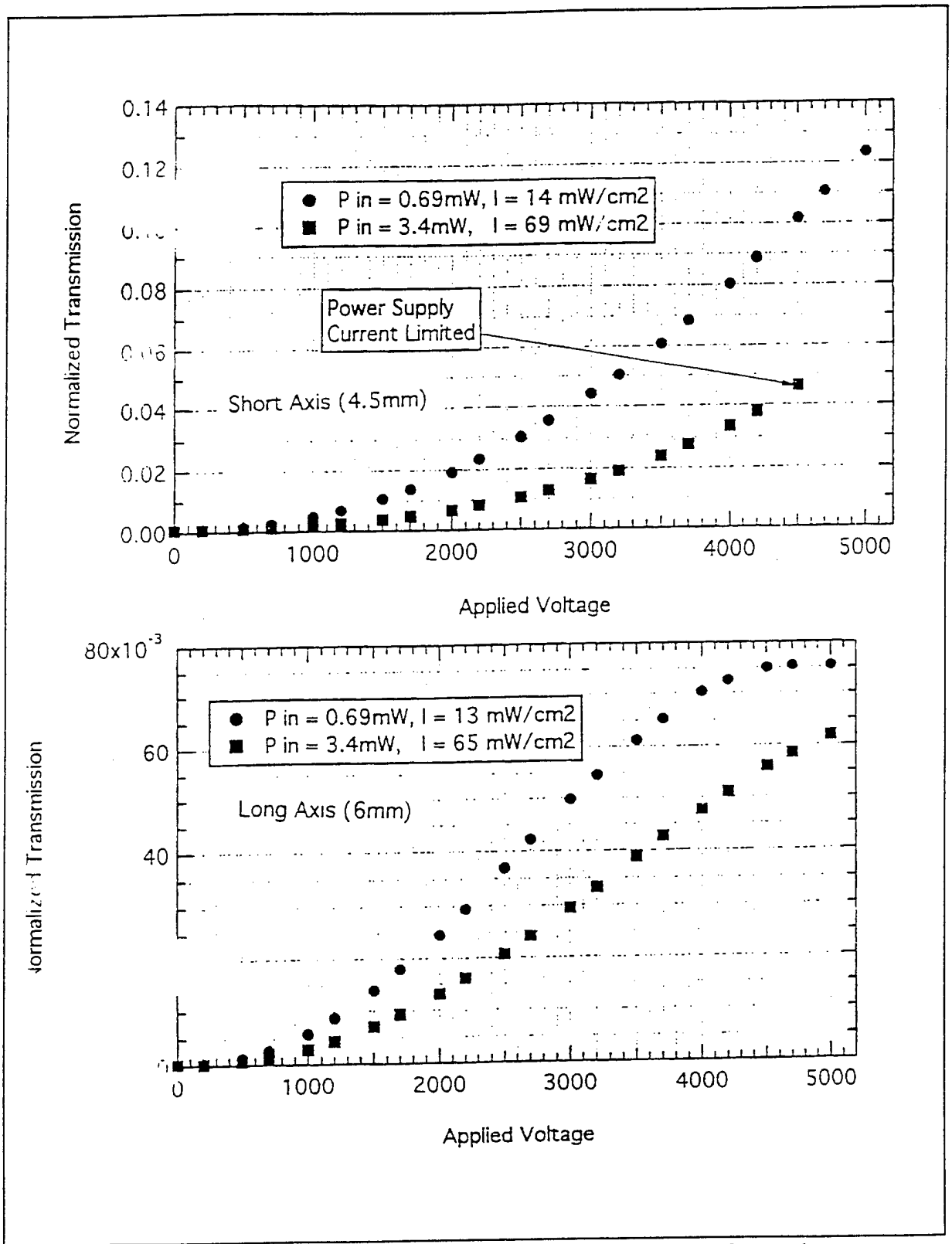

Figure 13 Normalized transmission versus applied voltage for CdTe:V crystal.

The optical limiting behavior displayed by this crystal is shown in Figures 14 (normalized transmission versus input intensity) and 15 (output intensity versus input intensity). For this experiment, the normalized transmission was measured as the input intensity varied from 10^{-4} W/cm^2 to almost 1 W/cm^2. A voltage of 4250 V was applied across the [111] faces. A 1.06 μm wavelength Nd:YAG laser with a spot size of approximately 400 μm was used, and the intensity was measured through the long axes (6mm) of the crystal. Taking into account the intensity change in the sample due to the absorption of 1.25 cm^{-1}, the transmission data was well fitted to equation (3) above, as shown by the solid curve in Figure 14. From the fitted data, the following parameters were determined:

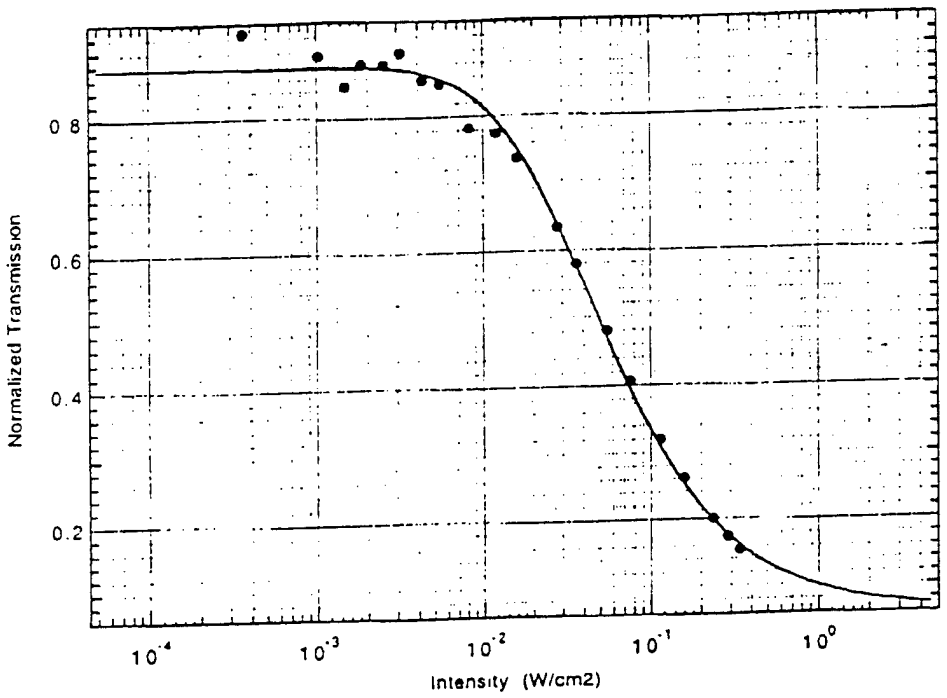

Figure 14 Normalized transmission versus input intensity for CdTe:V EOPL.

$$I_{in} / I_{out} \text{ (max)} = 0.875 \pm 0.10$$

$$\beta / \sigma = 45 \pm 5$$

$$\epsilon_p = 3.22 \pm 0.03$$

These measurements demonstrate the advantages of EOPL:

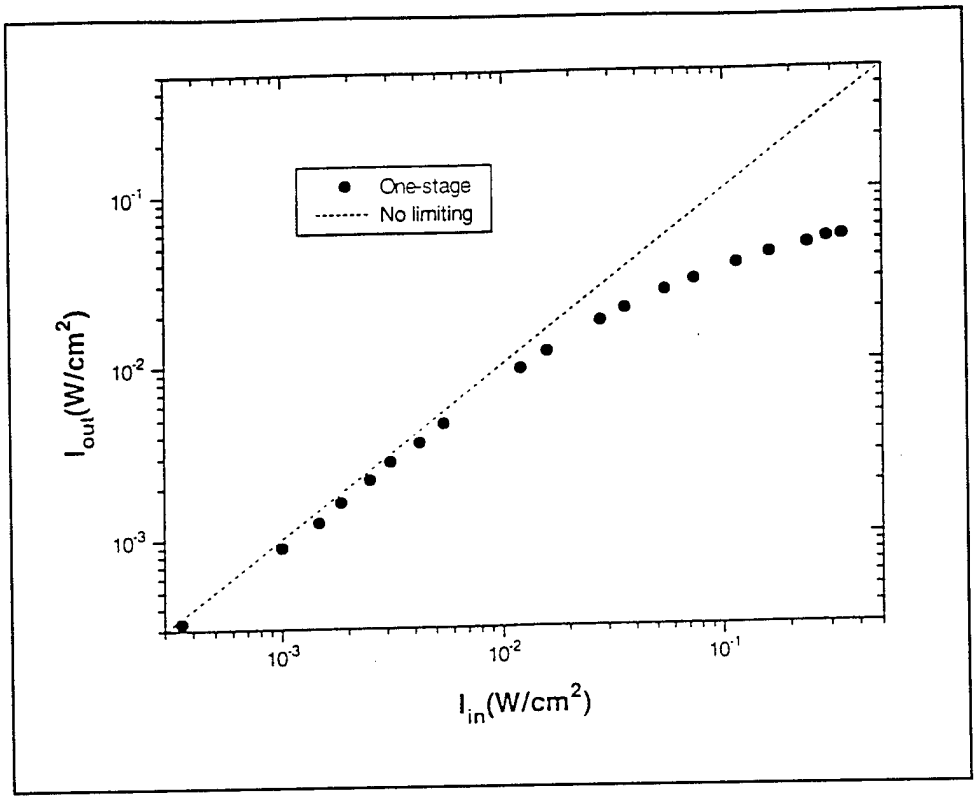

Figure 15 Output intensity versus input intensity for CdTe:V EOPL.

(1) The limiter has a very low threshold intensity;

(2) The aperture (4.5 mm^2) and the angular aperture can be relatively large;

(3) The device wavelength is agile. For CdTe, wavelengths from 0.9 μm to 1.6 μm can be used; using other II-VI materials, the wavelength range can be extended from the visible to beyond 2 μm;

(4) The device works for incoherent light and only limits over the area exposed to the jamming beam: The remainder of the aperture remains open; and

(5) The device does not require any electrical feedback circuitry.

As mentioned above, we encountered problems with voltage breakdown of the CdTe:V crystals at voltages of approximately 2-3kV. We had determined that this breakdown was due to voltage arcing because of moisture in the crystal's environment. Therefore, we have designed a dewar with transparent windows for transmission of radiation in which to place the CdTe:V crystal. The dewar was evacuated and flushed several times with dry N_2 gas. Nitrogen was added to the dewar and the dewar was sealed. Using this method, we were able to apply

between 7 and 8 kV across the crystal without the occurrence of breakdown. Therefore, using our experimental setup, we can easily achieve the half-wave voltage of 4.9 kV needed for optimal operation. It was previously determined [19] that the optimal voltage for optical limiters employing GaAs at $\lambda = 1.06\mu m$ and D=L is 9.3kV. However, breakdown is common for such a high voltage and optimal operation is difficult to achieve.

5.5 Two-Stage EOPL Design

We have theoretically designed and evaluated a two-stage EOPL design. The optical power limiter described by T. Y. Chang et al [19] used a CdTe:In crystal that was prepared with an anti-reflection coating and therefore was evaluated under ideal conditions. We believe that our CdTe:V crystals would show performance as good as or better than the CdTe:In if evaluated under similar conditions. At the present time, however, the CdTe:In data presented by Chang et al shows the best performance. Therefore, we used this data to analyze the performance of our novel two stage design.

In the experiments on CdTe:In performed by Chang et al, a pair of Glen-Thompson polarizers were used because of their high extinction ratio of ~ 60dB. The laser beam was focused to $\sim 100\mu m$ inside the crystal. The crystal was a 5mm cube and the two optical surfaces were broadband anti-reflection coated. High resistivity of 10^9 Ω-cm was achieved in this crystal owing to the compensation of shallow levels by the indium dopant. The high resistivity allowed the half-wave voltage $V_\pi = 4.9$ kV to be applied without the occurrence of thermal run-away.

Figure 16 shows the experimental results from this EOPL. The solid dots show the transmission (left y axis) as a function of the normalized input intensity. The open circles show the output intensity (right y axis) versus normalized input intensity. The diagonal dashed line (constant transmission) predicts the output intensity when there is no limiting. One can see clearly the limiting effect from these plots. As the input intensity increases, the optical density (O.D.) of the EOPL increases from 0 to 3, cutting the intensity by up to 3 orders of magnitude. However, the O.D. is saturated at approximately 3 as the intensity increases beyond 10^{-2} I_{max}. This saturation poses a formidable problem for the one-stage EOPL. For a maximum input intensity of 10^2 W/cm^2, the output intensity is of the order of 0.1 W/cm^2. This output intensity exceeds the upper limit (typically of the order of 10^{-3} W/cm^2) of most far infrared (FIR) detectors. In order to make a practical limiter, it must be able to cut the input intensity by a factor up to 10^5 when the input intensity approaches 10^2 W/cm^2. As we shall discuss in the next section, this can be achieved by a two-stage EOPL design.

The minimum leakage through the EOPL (approximately 10^{-3} at high input intensity) was 3 orders of magnitude higher than that attributable to the polarizers (10^{-6}). This is due to a number of factors related to the crystal including induced birefringence, inhomogeneity, and scattering of the incident beam into the dark region of the crystal. There is room to improve the material further with regard to these aspects. However, it is extremely difficult to cut the leakage to 10^{-5} (i.e., further reduction by a factor of 100), as required for a practical limiter.

Nevertheless, with this 10^{-3} one-stage leakage, the overall leakage can be cut down to 10^{-5} with a two-stage EOPL design.

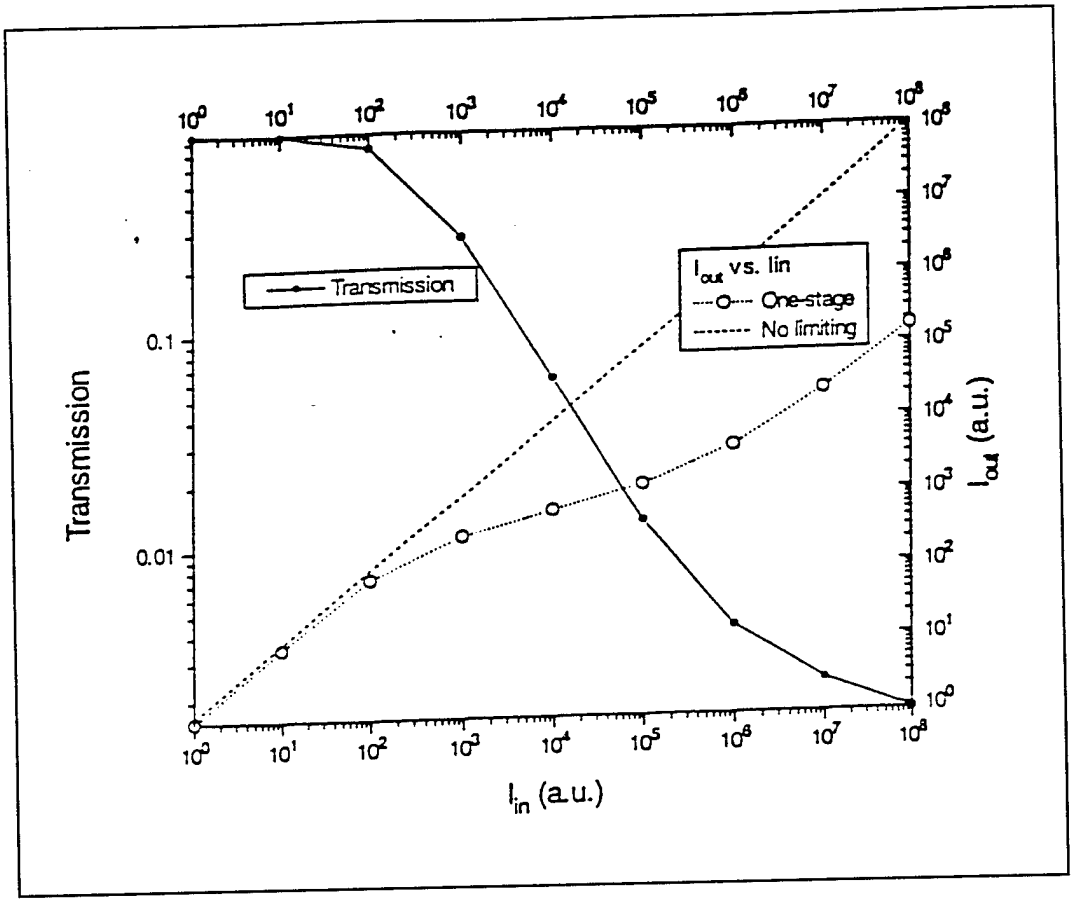

Figure 16 Experimental results of EOPL.

The limitation on one-stage EOPL can be overcome by stacking two such EOPLs in series, as illustrated in Figure 17. The polarizer between the two crystals serves as the analyzer for the first stage and as the polarizer for the second stage. Using the one-stage EOPL data shown in Figure 16, the performance of such a two-stage EOPL is calculated and plotted in Figure 18. In the two-stage EOPL, the incident light is rejected twice. Each stage can cut down the intensity by a factor of up to 10^3. At an input intensity of 100 W/cm^2, the O.D. of this two-stage EOPL reaches ~ 5, reducing the intensity to $\sim 10^{-3}$ W/cm^2, which is in the working range of most FIR detectors. Although the output intensity I_{out} still increases slightly with the input intensity I_{in} (not clamped to a constant value), this EOPL is certainly practical because I_{out} falls in the detectable range.

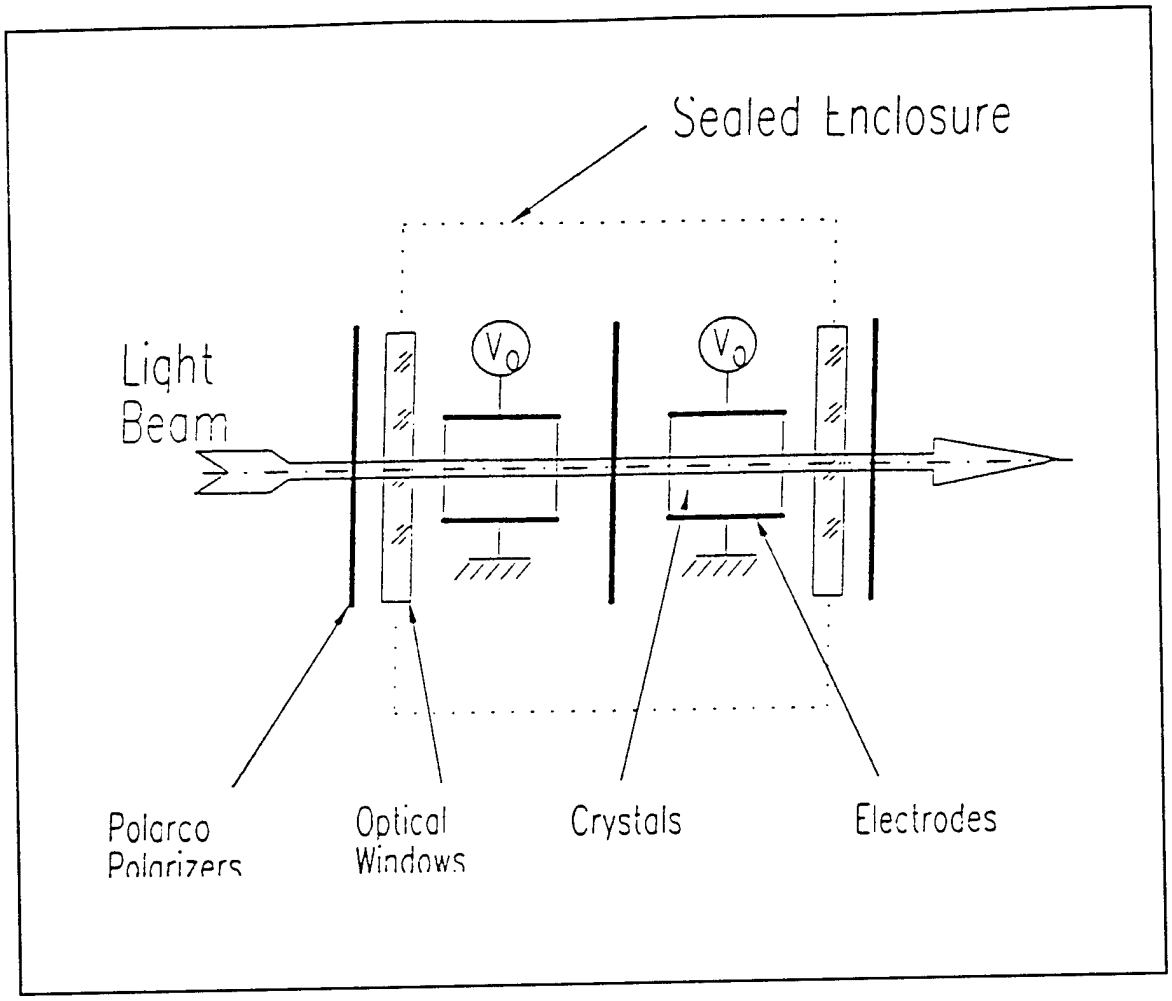

Figure 17 Two-stage EOPL design.

A prototype of such a two-stage EOPL has been tentatively designed. A detailed drawing of this prototype device is shown in Figure 19 and the parts list is shown in Figure 20.

The following addresses several practical problems with the two-stage EOPL including angle of view, insertion loss, material parameters, and packaging:

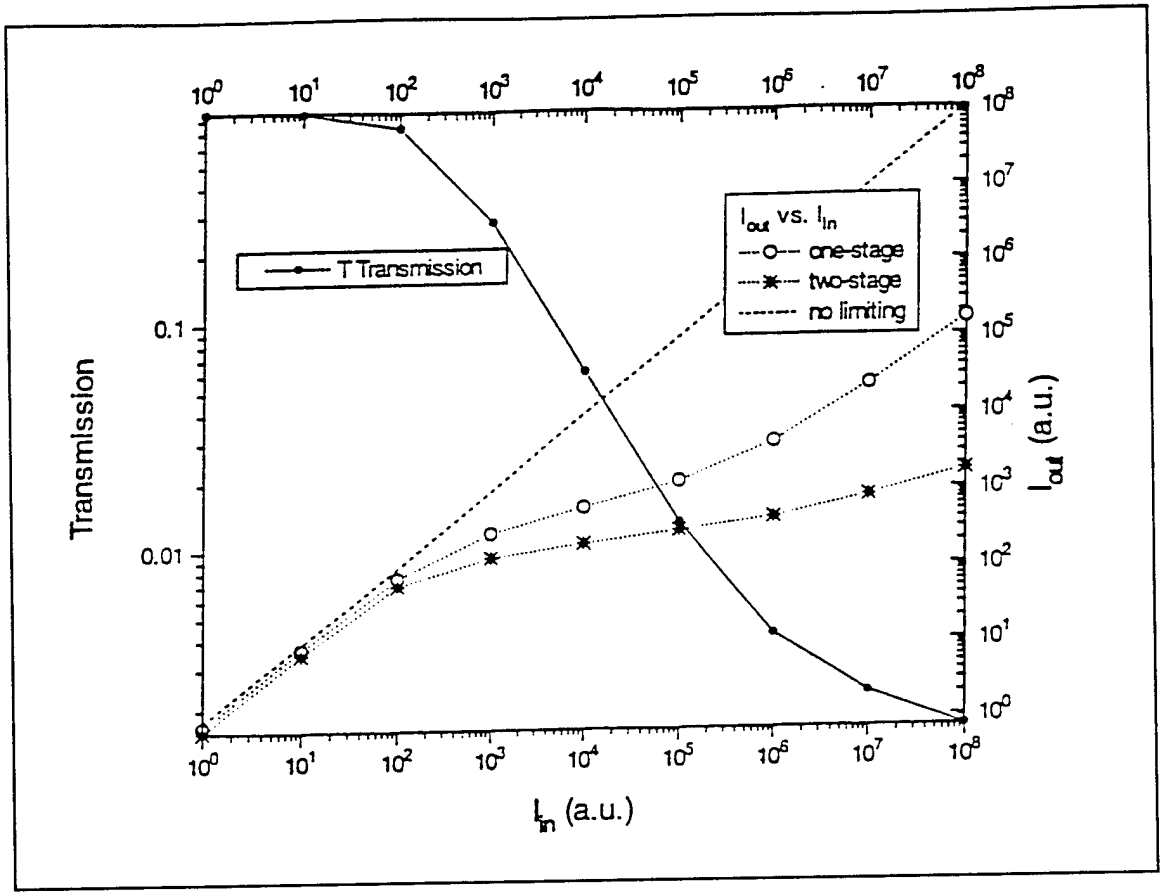

Figure 18 Calculated performance of two-stage EOPL.

In order to achieve wider field of view, Glen-Thompson polarizing prisms were used [19]. However, this type of polarizer requires a high length/aperture ratio (≥ 2.5) to achieve a large field angle (full angle of $\sim 15°$). For an aperture of 5 mm, the length is at least 15mm. This will make the field angle of a two-stage EOPL unacceptably small. Recently, Corning Inc. has commercialized a new series of near infrared (NIR) dichroic glass polarizers called Polarcor. Polarcors appear more suitable for EOPL applications. They have a large field angle of $\pm 15°$ with a thickness of only 0.5 mm. Their extinction ratio is as high as 10^{-4} within a 400nm bandwidth. This extinction ratio should not degrade the EOPL performance since the minimum crystal-originated leakage is $\sim 10^{-3}$. The safe intensity level of the Polarcor is 25W/cm^2 for blocked CW light, somewhat lower than that of Calcite polarizing prisms (50-100 W/cm^2), but still practical.

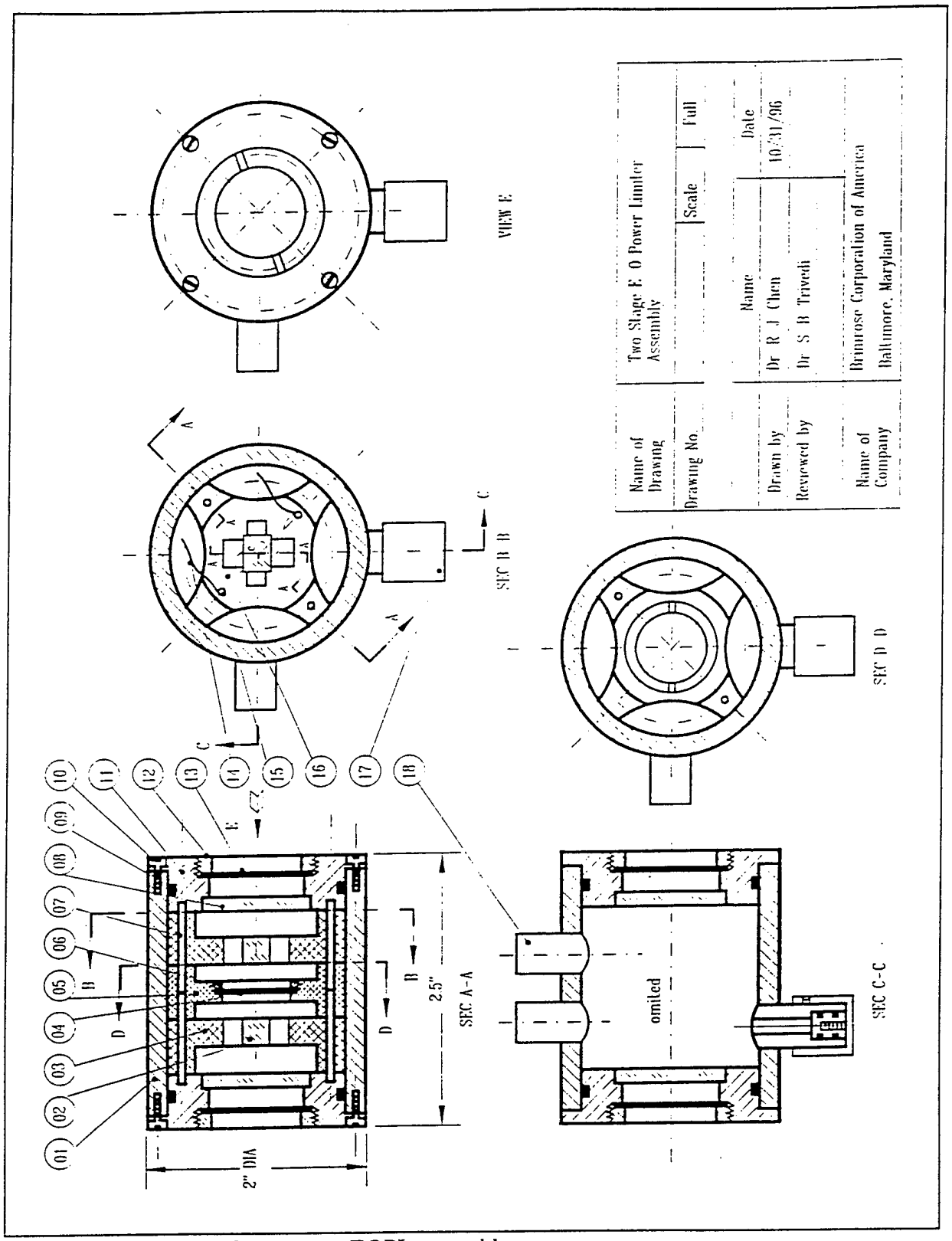

Figure 19 Drawing of two stage EOPL assembly

Part No.	Name of Parts	Quantity	Material	Notes
01	Cell Body	1	Aluminum	
02	E-O Crystals	2	II-VI	8.5 x 6.3 x 6.3 mm^3
03	Crystal Holders	2	PTFE Teflon	for its small ε =2.0
04	Center Polarizer	1	Polarcor	0.75" DIA x 0.5 mm thick
05	Center Polarizer Holder	1	PTFE Teflon	
06	Center Polarizer Retaining Ring	1	PTFE Teflon	
07	Dowel Pins	4	Stainless Steel	1/16" DIA
08	Window Glasses	2	Fused Silica	1" dia x 3 mm thick
09	O-rings	2	rubber	
10	Retaining Screws	8	Stainless Steel	
11	End Caps	2	Aluminum	
12	End Polarizer retaining Nuts	2	Aluminum	
13	End Polarizers	2	Polarcor	1" DIA x 0.5 mm thick
14	Leads to Terminals	4	insulated Copper	
15	Leads Anchors	4	Copper	
16	Leads to Crystals	4	Copper	
17	Purging Valve	1	Aluminum	Commercially Available
18	Electric Terminals	2		

Figure 20 Parts list for drawing in Figure 18.

To achieve a large field of view, the two crystals should be brought as close together as possible. However, a polarcor in between may present problems if it is too close to the crystals. Since a polarcor is conducting, it will draw electric field lines out of the crystal and thus distort the field in the crystal. In fact, even butting insulators (with high dielectric constants) to the crystal surfaces perpendicular to the electrodes will draw field lines out of the crystal, and thus should be avoided. Also, since a polarcor converts the blocked light into heat, it could either overheat itself or locally heat up the crystal (which is a thermal insulator) and thus distort the wave front. For these reasons, there should be a gap (say, 3-5mm) between the polarcor and each of the two crystals. Even with two such 5mm gaps, the two-stage EOPL (with 5mm-cube crystals) can still have a full field angle of 15° (limited by the field angle of the Polarcors). It should be noted that the field of view for such a device is limited by the polarizers and not by the two-stage design.

In order to prevent electrical break-down between the electrodes, the two crystals should be enclosed in a sealed cell filled with dry gas (or some other fluid). Since there is no fluid that can match the refractive indices of the crystals($n \cong 3$) and the rest of the optics ($n \cong 1.5$), dry gas is preferred. Dry N_2 is inexpensive and works well. A commercially available miniature

vacuum valve can be sealed to the cell body and used to purge the cell. In order to reduce the insertion loss, all the optical surfaces, especially those of the two crystals, must be broadband anti-reflection (AR) coated. The cell body should be a good thermal conductor in order to keep the temperature uniform inside the cell and to efficiently remove the heat inside the cell. Aluminum is a good choice. An unblocked path should be maintained for the gas to convert heat from the polarcor to the cell body. The two end polarizers should be placed outside the cell to reduce the heat generated inside the cell. These two end polarcors, as well as the two optical windows, can be placed further away from the crystals without reducing the angle of view, as long as their apertures are large enough.

Next, we examine the crucial material parameter β/σ_{dark} in the light of T. Y. Chang's model, described in section 3.3. Notice that the transmission (or O.D.) is determined by the product $(\beta/\sigma_{dark})I_{in}$. If (β/σ_{dark}) is increased by a factor of m, then the same O.D. can be reached at an input intensity m times smaller. However, since the O.D. is saturated for I_{in} higher than a certain level for the sample shown in Figure 16, increasing (β/σ_{dark}) will not raise the maximum O.D. but just saturate O.D. at a lower I_{in}. This behavior is illustrated in Figure 21 where one-

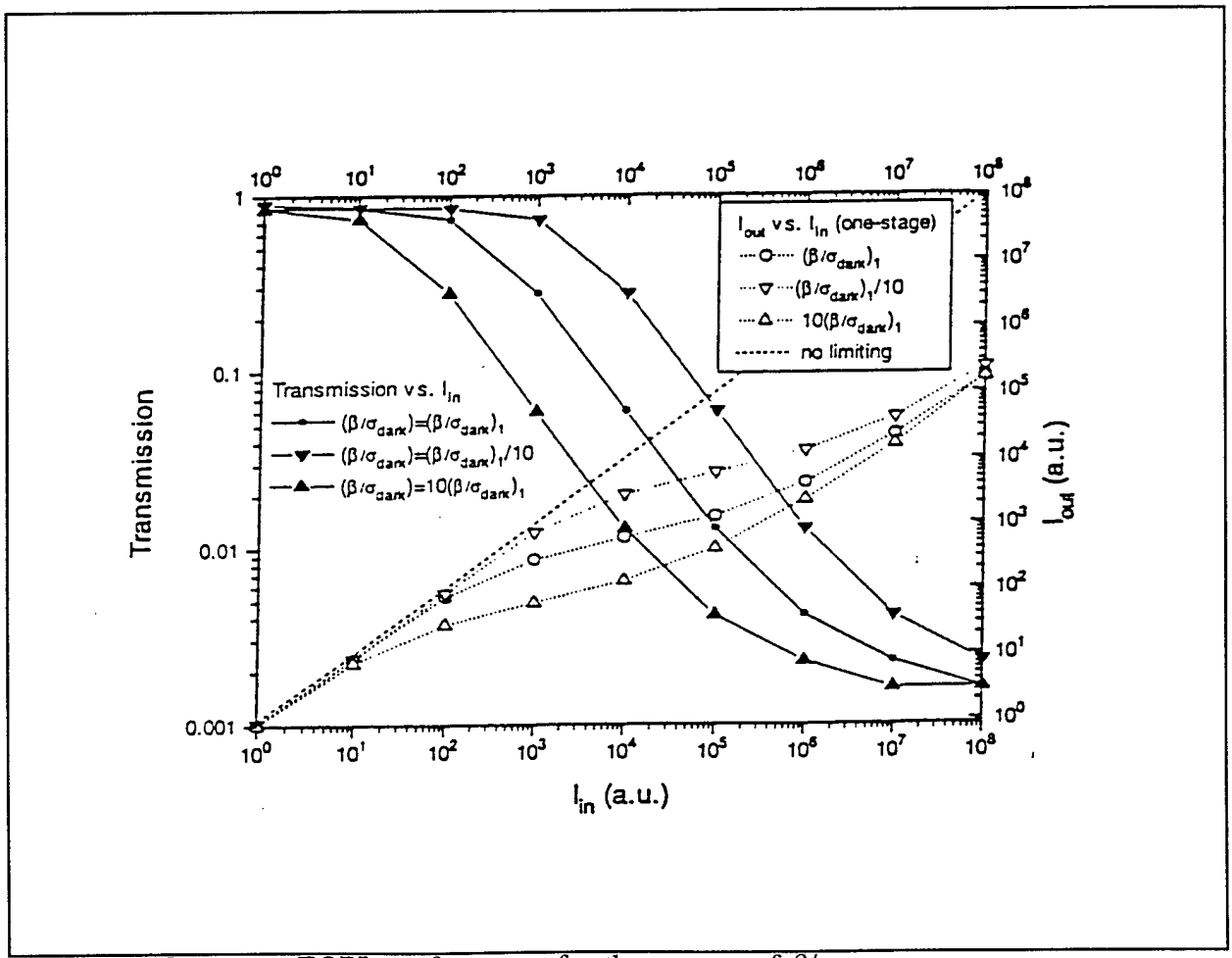

Figure 21 One-stage EOPL performance for three cases of β/σ_{dark}.

stage transmission and output intensity for the sample shown in Figure 16 are plotted against I_{in} for three cases:

(i) $(\beta/\sigma_{dark}) = (\beta/\sigma_{dark})_1$;

(ii) $(\beta/\sigma_{dark}) = 10(\beta/\sigma_{dark})_1$;

(iii) $(\beta/\sigma_{dark}) = (\beta/\sigma_{dark})_1/10$.

Clearly, increasing (β/σ_{dark}) beyond $(\beta/\sigma_{dark})_1$ (i.e., case ii) does not improve performance, but just attenuate the light more at lower intensities. Obviously, *the optimum (β/σ_{dark}) should be such that the corresponding O.D. just begins to saturate at the maximum working I_{in}* ($25 W/cm^2$ for the first stage, 25×10^{-3} W/cm^2 for the second stage).

The best way to achieve a high (β/σ_{dark}) is to minimize σ_{dark} so that β can be kept as small as possible. This is essential to the improvement of the transmission. A combination of higher β and higher σ_{dark} is undesirable. A higher β means a higher doping density, and hence higher absorption and scattering losses. A higher σ_{dark} means stronger ohmic heating and even thermal run-away.

In order to achieve a high throughput, the crystal apertures should be as large as possible. As mentioned before, it is reasonable to choose the crystal height (D) equal to the length (L) so that the half-wave voltage ($V_\pi = 4.9$ kV) is not too high. To keep the insertion loss acceptable, L and hence D is limited to $\leq$ 8 mm. Since there is no limitation on the crystal width (W), it is advantageous to make W wider than D (e.g., W= 4D/3 to give an aspect ratio of a television screen).

Finally, we discuss another practical problem. When the beam is not tightly focused (or the scene is very bright) such that most of the crystal aperture is strongly illuminated, the total resistance of the crystal can become so low that the current through the crystal exceeds the tolerable level I_t (corresponding to a maximum tolerable heating power $V_\pi I_t$). This can be avoided by masking the circumference of the crystal aperture. The masked portion of the crystal functions just like a constant resistor. This reduces the effective aperture height and thus is undesirable. A better solution is to regulate the voltage V_o applied to the crystal as follows: (i) $V_o = V_\pi$ when the current $I \leq I_t$; (ii) $V_o = V_\pi I_t/I$ when $I \geq I_t$. In case (ii), the voltage V_o is kept as high as possible without causing thermal run-away.

6.0 Conclusions and Phase II Plan

During this phase I project, we successfully developed and produced CdTe:V crystals for EOPL. The crystals exhibited good transmission over the wavelength range from 900 nm to 1500 nm, resistivity on the order of 10^8 to 10^{10} Ω-cm, and high photoconductivity. Structural analysis using an infrared microscope of the bulk structure revealed the high quality of these crystals. Ultimately, we achieved excellent optical limiting performance using CdTe:V. We demonstrated a limiter with: (1) a very low threshold intensity; (2) a relatively large angular aperture; (3) agile wavelength sensitivity; (4) insensitivity to the coherence of the input radiation; and (5) no electrical feedback circuitry.

There are still a few possible areas for improvement in the material properties of the CdTe:V crystals. Growth of CdTe oftentimes results in material with a high concentration of complex point defects because of stoichiometric problems. Therefore, further investigations into improving the microstructure of the crystals through growth and processing techniques is necessary to obtain superior EOPL material. Improvements in microstructure would also lead to improvements in the photoconductivity constant (β) and response time (τ).

As discussed previously, an appropriate concentration of deep level impurities is required to obtain a balance between the absorption of the crystal and the photoconductivity and field shielding properties of the crystal. Within the time frame of this phase I project, we grew CdTe crystals with two concentrations of vanadium: $1x10^{19}$ cm^{-3} and $5x10^{19}$ cm^{-3}. In the past, we have seen the field shielding effect in indium doped CdTe with a dopant concentration of only 10^{13} cm^{-3} [1]. Therefore, we plan to investigate the effect of using a lower concentration of vanadium to produce the necessary concentration of deep level traps in the CdTe crystals. The effect of using a lower dopant concentration could significantly increase the transmission through the crystal while still maintaining adequate photoconductivity and field shielding properties. Furthermore, the "as-received" vanadium that was used during this project was 99.98% pure. Given the time frame in which we were working, we were unable to further purify the vanadium. Since impurities contained within the vanadium may contribute to increased absorption in the CdTe crystal, we plan to investigate the effect that purification of vanadium prior to crystal growth will have on the overall properties of the CdTe:V crystals.

The power limiting results that we presented in this report were obtained on crystals in which no anti-reflection coating was used. As such, scattering of the incoming light into the dark regions of the crystal can significantly degrade device performance. Therefore, we plan to apply an appropriate anti-reflection coating to the CdTe:V crystals and investigate the resulting improvements to device performance.

During this phase I project, we have developed an innovative design that could extend the range of input intensities over which an optical power limiter can operate: a two-stage EOPL. In this time period, we have theoretically designed and evaluated this two-stage design. During phase II of this project, we plan to evaluate this design in much greater detail and eventually design and build an actual two-stage EOPL device. This process will involve several steps including evaluation of potential problems including material parameters, device parameters and packaging. We believe that such a design will represent a new state-of-the-art in optical power limiting.

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